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Determination of the Region of Stabilization of Low-Cycle Fatigue HSLE Steel from Test Data

Bojana Aleksić, Vujadin Aleksić, Abubakr Hemer, Ljubica Milović and Aleksandar Grbović

Introduction

The most important role in fracture of the materials of machine parts and structures has various types of fatigue. The fatigue life of reliable components of engineering elements, such as bearings, which are exposed to variable load over the life of exploitation, can be estimated by the analysis of the behaviour that includes processing of the data on loading, geometry and the material selected for manufacture of the bearings, both by simulation and experimentally [1–5].

Steel, NN-70, selected in this study to investigate the experimental behaviour affected by fatigue loading, among other things, is used in shipbuilding and for manufacture of pressure vessels as well. The experiment was conducted using smooth round specimens made of steel NN-70 as parent material (PM). When selecting stabilized hysteresis as a representative of all of stabilized hysteresis for one strain level, and for the further processing of low-cycle fatigue test results, the recommendations of standards [6, 7] have been used as well as the methodology

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based on which linearity of the stabilization regions of low-cycle fatigue was numerically determined [8].

Background and Characteristics of Steel NN-70

Parent material (PM) used to make the test specimens was a plate of the dimensions (45 × 205 × 353) mm made of low-alloy high-strength steel NN-70 with properties shown in Tables 1 and 2.

Steel NN-70 is the Yugoslav version of American steel HY-100 and is intended for manufacture of ship structures, submarines and pressure vessels by welding, where the required toughness is extremely important. The technology of manufacture and thermomechanical processing (TMCP steels [10]) of the steel called Nionikral-70 is the result of joint research work of the metallurgists of Military Technical Institute in Žarkovo (VTI) and the steelworks "Jesenice" from Jesenice [11], in the early 90s of the last century. It was made in the electric furnace, cast in brams, subsequently rolled into slabs and finally the sheets of various thicknesses. Due to some of its characteristics, it is classified among the fine-grained steels. The process of hardening is the combination of classical improvement (quenching and tempering) with grain refinement in accordance with selected chemical composition, by micro-alloying and appropriate deposition [12]. In determining the limit values of carbon and other alloying elements for the analysis, bearing in mind the purpose of the steel, care was taken to meet the requirements for the combination of characteristics such as strength, ductility, resistance to crack initiation and propagation, the stability of these properties at low temperatures, good resistance to fatigue and stress corrosion, and good workability and weldability [12]. Steel NN-70 is intended to be shaped by welding, so that after it was successfully mastered, its suitability for welding was also subjected to assessment [11].

Table 1 Chemical composition of NIONIKRAL 70, %wt [8]

C	Si	Mn	P	S	Cr
0.106	0.209	0.220	0.005	0.0172	1.2575
Ni	Mo	V	Al	As	Sn
2.361	0.305	0.052	0.007	0.017	0.014
Cu	Ti	Nb	Ca	B	Pb
0.246	0.002	0.007	0.0003	0	0.0009
W	Sb	Ta	Co	N	–
0.0109	0.007	0.0009	0.0189	0.0096	–

Table 2 Mechanical properties of NIONIKRAL 70 [8]

Property	PM
Ultimate tensile strength, MPa	855, rounded value
Yield strength, MPa	815, rounded value
Elastic modulus, GPa	221.4, dynamic, LCF
Impact toughness, J	97, rounded value, 20 °C
E initiation, J	40, rounded value, 20 °C
E propagation, J	57, rounded value, 20 °C
HV30, plate of PM	257, mean value, plate of PM
HV10, stick for LCF specimen [9]	257, mean value, specimen of LCF

Testing of Steel NN-70 at Low-Cycle Fatigue

From the necessity to assess the low-cycle fatigue life, and in order to determine the fatigue characteristics of the material, the test of resistance of the parent material (PM) of steel NN-70 to low-cycle fatigue was carried out. Preparation of the test of resistance of steel NN-70 to low-cycle fatigue consisted of making smooth cylindrical specimens, Fig. 1 item 1, and tool for placing the specimens in the tearing-machine jaw, Fig. 1 items 2 and 3, and check of the target static tensile properties of steel NN-70, Table 2.

The procedure for determination of the low-cycle fatigue characteristics and geometry of cylindrical smooth specimen as well, Fig. 1 item 1, is defined by the ISO 12106:2003(E) [6] and ASTM E 606-04$^{\varepsilon}$ [7] standards.

Fatigue test was conducted on a universal MTS system (Material Testing System—Universal hydraulic dynamic tearing machine of 500 kN) for the material testing, schematically presented by photos in Fig. 2.

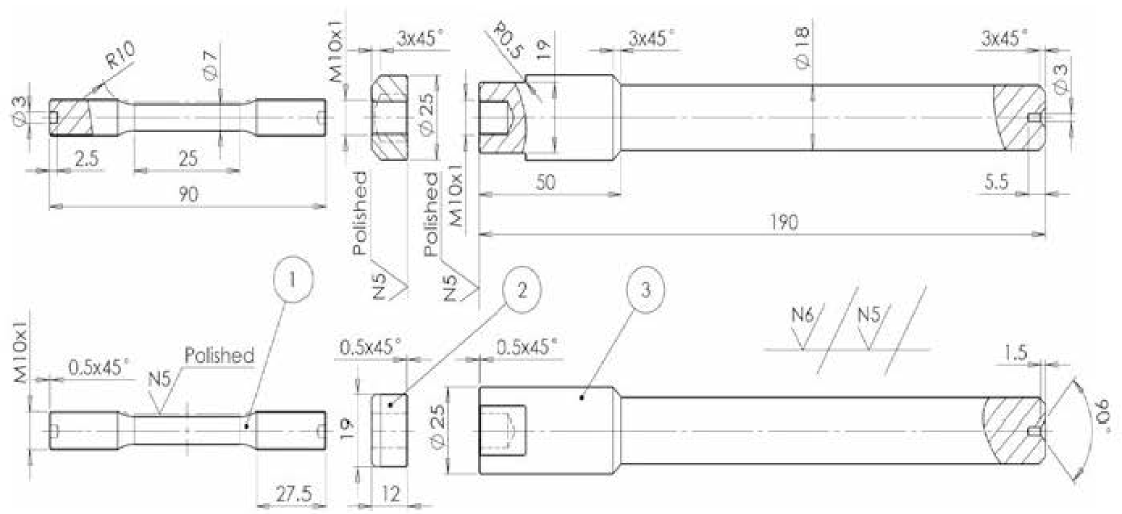


Fig. 1 Specimen and specimen holder for testing LCF of steel NN-70 [8]. Item 1, LCF specimen, NN-70, D = 7 mm; item 2, Jam nut, 42CrMo4; item 3, Grip holder, 42CrMo4.

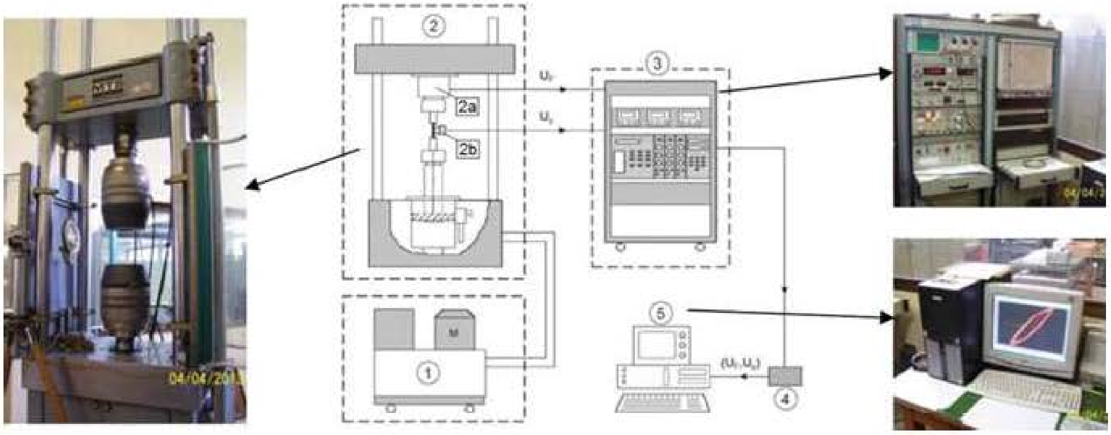


Fig. 2 MTS universal system for the material testing, 1—Hydraulic aggregate, 2—Pulsating device, 2a—MTS force-feeding device, 2b—MTS extensometer, 3—Control system, 4—A/D convertor, 5—PC

Used MTS force-feeding device, Fig. 2 item 2a, with linear characteristics $F[kN] = F[V] \cdot 10$, and MTS extensometer with measuring length of $L_0 = 25$ mm, Fig. 2 item 2b with linear characteristics $\varepsilon[\%] = \varepsilon[V] \cdot 0.2$, are graphically presented in Fig. 2.

Low-cycle fatigue tests were performed on a series of smooth specimens made of steel NN-70, with semi-amplitudes of controlled and fully reversible strains, $\Delta\varepsilon/2 = 0.35$, 0.45, 0.50, 0.60, 0.70 and 0.80 ($\Delta\varepsilon/2 = \text{const}$, $R_\varepsilon = \varepsilon_{min}/\varepsilon_{max} = -1$).

Numerical Determination of the Region of Stabilization

Most of the materials, at low-cycle fatigue and at a certain level regulated strain, achieve a so-called stabilized condition. It is a condition when the height of the hysteresis loop expressed through a range of force of loading or stress slightly changes, Fig. 3 item 9.

The most common methods for determination of the number of cycles to crack initiation, N_f, are defined by the standards [6, 7]. New methods [8] for determination of the beginning and end of the crack initiation and establishment of linearity of stabilization regions are based on experimental data, by arbitrary selection of three cycles on the basis of which we can establish linearity that we maintain by filtering the data in the programme EXCEL, toward the beginning and end of the test. The results of established linearity in the areas of stabilization for steel NN-70 are shown in Table 3.

In this way we determine the initial, N_{bs}, and final, N_{es}, cycle of stabilization, i.e. the beginning and end of the crack initiation, Fig. 4a. Stabilized hysteresis, N_{s1}, Fig. 4b, is located in the middle of the region 9, Fig. 3, and is determined by the formula, $N_{s1} = N_{bs} + (N_{es} - N_{bs})/2$. This method of determination of the stabilized hysteresis, N_{s1}, is called "Method of the middle stabilization (ms)" [8]. In a similar

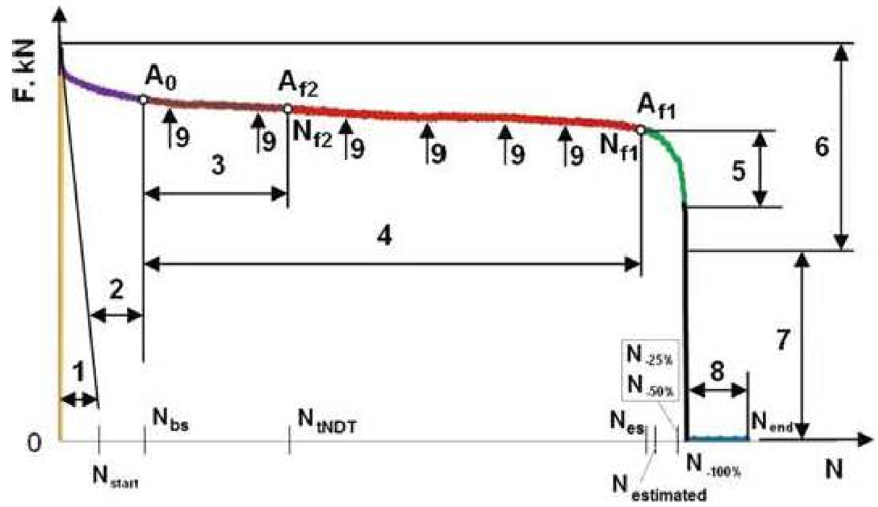


Fig. 3 Regions of low-cycle fatigue. 1—Adjustment of tearing machine, 2—Adaptation of tearing machine, tools and specimen, 3—Crack formation up to threshold of NDT, 4—**Stabilized state**, 5—Force drop of 25 % (ISO 12106:2003(E)) [6], 6—Force drop of 50 % (ASTM E 606-04) [7], 7—Force drop to F = 0, 8—Stoppage of tearing machine, 9—Height of hysteresis loop, N_{start}—Test start up, **F=max**, N_{bs}—Beginning of stabilization, A_0, mm, N_{tNDT}—threshold of the NDT, A_{f2}, mm, N_{es}—End of stabilization, A_{f1}, mm, $N_{estimated}$—force-drop assessment of an operator, N_{end}—Test termination, A_0—initial cross-section of the specimen (css), A_{f1}—css at the end of stabilization, A_{f2}—css at the threshold of the NDT

way, we can establish a cycle of appearance of a crack of 1 mm^2 surface area [13], which can be identified by the NDT methods, which is called the "threshold NDT method (tNDT)" [8], and then the cycle of stabilized hysteresis, N_{s2}, Fig. 4b, which is located in the middle of the region 3, Fig. 3, so that $N_{s2} = N_{bs} + (N_{tNDT} - N_{bs})/2$. This procedure was applied to other specimens as well, i.e. other strain levels, $\Delta\varepsilon/2 = 0.35$, 0.45, 0.50, 0.60, 0.70 and 0.80.

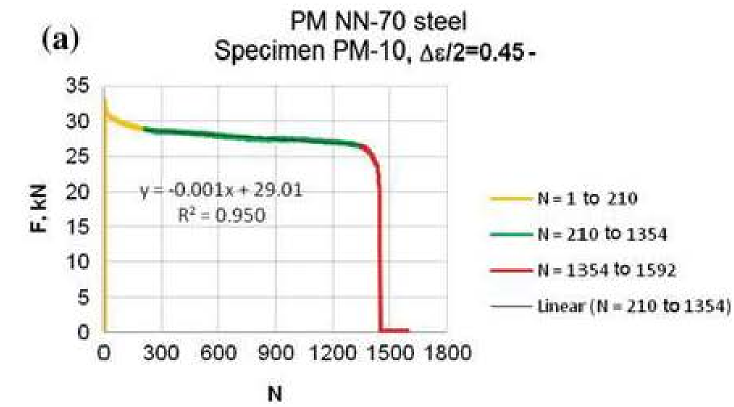
The accuracy of determination of the exponents and coefficients of cyclic stress-strain curve (**CSSC**) and basic curve of low-cycle fatigue (**BCLCF**) depends on accuracy of determination of linearity of stabilization region (for **7 samples**, determination coefficient, $\mathbf{R^2 = 0.85–0.98}$, Table 3) and for chosen method for determination of the stabilization curve it ranges as follows: for CSSC (for ms method for determination of $\mathbf{n'}$ and $\mathbf{K'}$ it is $\mathbf{R^2 = 0.66}$, and for tNDT method it is $\mathbf{R^2 = 0.62}$, Table 4, while for BCLCF (for ms method for determination **b** and $\boldsymbol{\sigma_f'}$ it is $\mathbf{R^2 = 0.77}$, and tNDT it is $\mathbf{R^2 = 0.78}$, Table 4) (for ms method for determination of **c** and $\boldsymbol{\varepsilon_f'}$ $\mathbf{R^2 = 0.72}$ **and for tNDT method** $\mathbf{R^2 = 0.68}$, Table 4).

After processing of registered data from all stabilized hysteresis of interest obtained using the methodology described, the curves of low-cycle fatigue for steel NN-70 are defined [14]:

Table 3 Data on the area of stabilization and characteristic cycles of LCF for PM of steel NN-70

Specimen	$\Delta\varepsilon/2\%$	Stabilization regions		Characteristic cycle of stabilization					
		y = F, kN; x = N	R^2	N_{bs}	$Nt_{NDT} = N_{f2}$	[b]N_{s2}	$N_{es} = N_{f1}$	[a]N_{s1}	
PM-01	0.35	y = −0.002x + 26.77	0.98	385	668	527	948	667	
PM-10	0.45	y = −0.001x + 29.01	0.95	210	535	373	1354	782	Figure 4
PM-03	0.50	y = −0.002x + 28.57	0.97	256	575	416	1271	764	
PM-06	0.60	y = −0.005x + 29.65	0.94	127	261	194	415	271	
PM-07	0.60	y = −0.006x + 29.84	0.90	97	210	154	293	195	
PM-05	0.70	y = −0.006x + 29.04	0.91	135	272	204	333	234	
PM-08	0.80	y = −0.013x + 30.47	0.85	82	142	112	165	124	

[a]Ns1 = Nbs + (Nes − Nbs)/2
[b]Ns2 = Nbs + (NtNDT − Nbs)/2



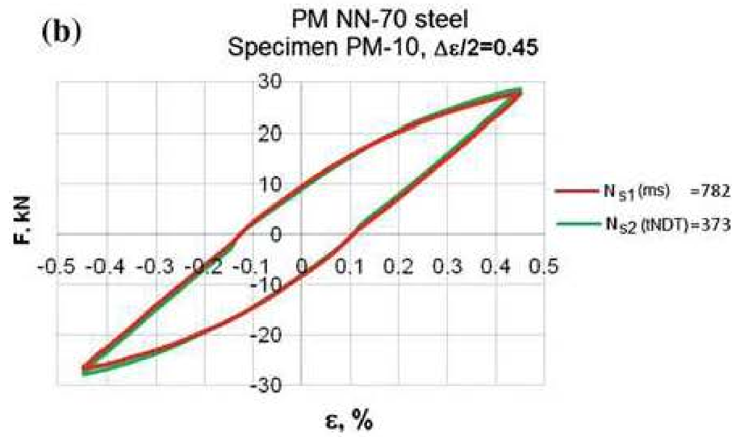


Fig. 4 **a** The region of stabilization, N = 210 to 1354 and **b** stabilized hysteresis in cycles Ns1 = Ns(ms) = 782 and Ns2 = Ns(tNDT) = 373

Cyclic stress-strain curves,

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}}:$$

$$\text{for } \underline{N_{s1}}: \frac{\Delta\varepsilon}{2} = \frac{1}{221378}\cdot\frac{\Delta\sigma}{2} + \left(\frac{1}{946.2}\cdot\frac{\Delta\sigma}{2}\right)^{\frac{1}{0.047}}, \quad (1)$$

$$\text{for } \underline{N_{s2}}: \frac{\Delta\varepsilon}{2} = \frac{1}{221378}\cdot\frac{\Delta\sigma}{2} + \left(\frac{1}{887.2}\cdot\frac{\Delta\sigma}{2}\right)^{\frac{1}{0.032}}$$

and

Basic curves of low-cycle fatigue,

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}N_f^b + \varepsilon_f' N_f^c:$$

$$\text{for } \underline{N_{s1}}: \frac{\Delta\varepsilon}{2} = 0.005105\cdot N_f^{-0.061} + 0.0612\cdot N_f^{-0.564}, \quad (2)$$

$$\text{for } \underline{N_{s2}}: \frac{\Delta\varepsilon}{2} = 0.005117\cdot N_f^{-0.065} + 0.0881\cdot N_f^{-0.695}$$

Table 4 Coefficient of determination (R^2) in processing of the data from LCF tests of PM of NN-70

		CSSC			BCLCF					
Specimen	$\Delta\varepsilon/2\%$	n'	K'	R^2	b	σ_f'	R^2	c	ε_f'	R^2
		1 2	1 2	1 2	1 2	1 2	1 2	1 2	1 2	1 2
PM-01	0.35	0.047 0.032	946.2 887.2	0.66 0.62	−0.061 −0.065	1130.1 1132.7	0.77 0.78	−0.564 −0.695	0.0612 0.0881	0.72 0.68
PM-10	0.45									
PM-03	0.50									
PM-06	0.60									
PM-07	0.60									
PM-05	0.70									
PM-08	0.80									

1 Method of the middle stabilization (ms), $N_{s1} = N_{bs} + (N_{es} - N_{bs})/2$
2 Threshold NDT method (tNDT), $N_{s2} = N_{bs} + (N_{tNDT} - N_{bs})/2$

Processing and Presentation of Test Results

As a result of low-cycle fatigue test on one specimen (one amplitude level of strain) there is a record in the program EXCEL which, using the tools available in EXCEL, can be further processed according to our requirements [8]. Before processing of the results it is possible to roughly determine the cycle in which there is a significant drop of force, $N_{estimated}$. To determine the indicators of low-cycle fatigue of the material presented by cyclic stress-strain curve (CSSC) and basic curve of low-cycle fatigue (BCLCF), the following analyses of the results of low-cycle fatigue tests were made:

1. For each amplitude level of strain (each specimen), by filtering the data, extreme values of the load forces and number of cycles were paired, and thus we eliminated the excess data. Both positive and negative values of the load forces were filtered.
2. The diagrams of extreme values of the load forces and number of cycles (F-N curves) were drawn for each amplitude level of strain.
3. The diagrams of determination of the areas of stabilization, Fig. 4a, were drawn (positive part of the F-N curves, the area of stabilization, was determined by linearization of the data on maximum tensile forces of load in low-cycle fatigue tests for each amplitude level of strain, Table 3). The areas of low-cycle fatigue and characteristic hysteresis were defined after the following:

   a. Determination of maximum force and starting cycle N_{start},
   b. Determination of the cycle of start of stabilization, N_{ss}, end of stabilization, N_{es}, threshold of NDT, N_{tNDT} and area of stabilization,

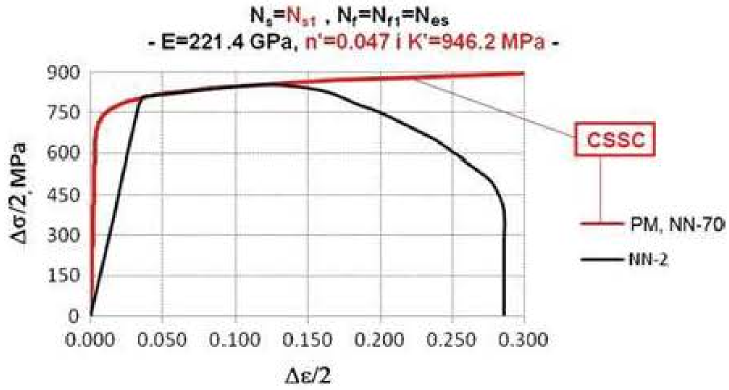
5. The characteristic data of stabilized hysteresis curves, Fig. 4b, for each amplitude level of strain were defined:

   a. Extreme values of load force F_{smax} and F_{smin} were read.
   b. The spots of intersection of the hysteresis curve and positive part of strain axis were established in EXCEL (coefficients of the straight line, m and b [8] were determined). This can be done graphically [4], too, in some of the programmes for precision drawing. $\Delta\varepsilon_p/2$, $\Delta\varepsilon_e/2$, $A_0 = D^2 \cdot \pi/4$ (3), $F_{mean} = (\left|F_{smak}\right| + \left|F_{smin}\right|)/2$ (4) i $\Delta\sigma/2 = F_{mean}/A_0 \cdot 1000$ (5) values were calculated.

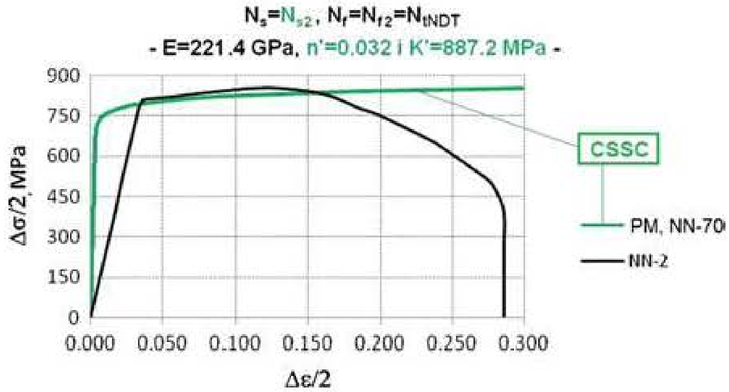
6. The data on all amplitude levels of strain were classified, cyclic stress-strain curves and basic curves of low-cycle fatigue were constructed [8, 15] and cyclic versus monotonous stress-strain curves compared, Figs. 5 and 6:

   a. The exponents and coefficients were determined using linearized step function, n′ and K′.
   b. The exponents and coefficients were determined using linearized elastic component, b and σ'_f. The exponents and coefficients of linearized plastic component, c and ε'_f, were determined.

Fig. 5 Comparison of cyclic (CSSC) and monotonous stress-strain curve of PM of NN-70 steel



(a) $N_f = N_{f1}$ (End of stabilization [8])

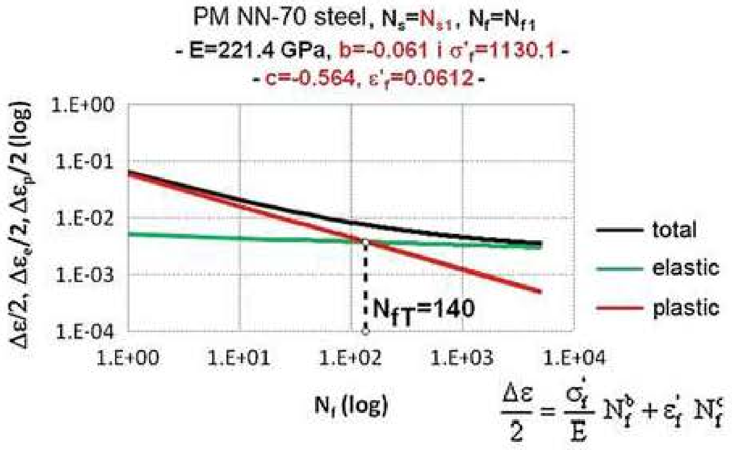


(b) $N_f = N_{f2}$ (threshold of NDT [8])

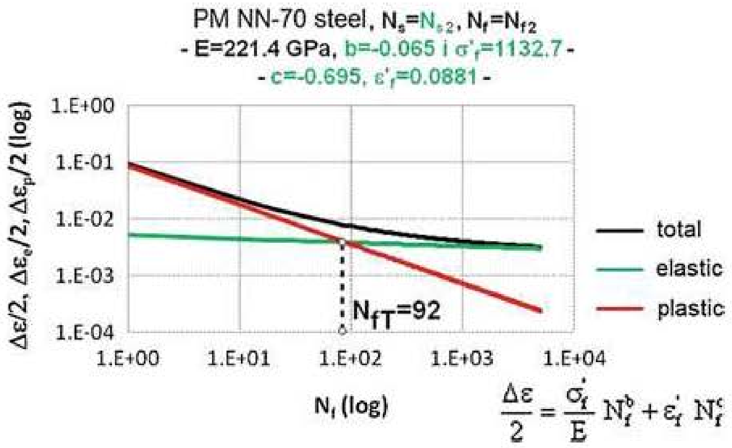
7. The data on cyclically stress-strain curves, Fig. 5a, b, and basic curves of low-cycle fatigue, Fig. 6a, b, were classified for the group of selected stabilized hysteresis, N_{s1} and N_{s2}, in order to construct them [8], and finally,
8. Transition life, N_{fT}, was determined for a group of selected stabilized hysteresis, N_{s1} and N_{s2}, Fig. 6a, b and Table 5 [8].

Conclusions

The theoretical, experimental and numerical research of the behaviour of low-alloy high-strength steels exposed to loading induced by low-cycle fatigue that are described in this paper are very complex research task. Extensive theoretical studies have required synthesis of knowledge in multiple engineering fields and disciplines, and numerical and experimental studies are an important part of this work. One of the goals of the research imposed itself during the processing of the results of experimental investigations, and is expressed through improvement of the methodology and methods of processing of the test results in order to establish a



(a) $N_f = N_{f1}$ (End of stabilization [8])



(b) $N_f = N_{f2}$ (threshold of NDT [8])

Fig. 6 Basic curve of low-cycle fatigue of PM of NN-70 steel

Table 5 Transition life of PM of steel NN-70

PM, NN-70	E, MPa	221378	Elastic part		Plastic part		
	N_f	N_s	b	σ'_f	c	ε'_f	N_{fT}
$N_{s1} = N_{ps} + (N_{ks} - N_{ps})/2$	$N_{ks} = N_{f1}$	N_{s1}	−0.061	1130.1	−0.564	0.0612	140
$N_{s2} = N_{ps} + (N_{pNDT} - N_{ps})/2$	$N_{pNDT} = N_{f2}$	N_{s2}	−0.065	1132.7	−0.695	0.0881	92
Transition life			$N_{fT} = \left(\frac{\varepsilon'_f \cdot E}{\sigma'_f}\right)^{\frac{1}{b-c}}$ (6)				

N_{fT} is transition life of PM of steel NN-70, and we calculated it for two different methods

universal methodology for assessment of the behaviour of materials affected by low-cycle load. The results of experimental investigation have given us important information about the understanding of fatigue behaviour of HSLA steel, NN-70, and the newly applied methods and recommendations of standards as well have enabled the precise determination of characteristic stabilized hysteresis for each strain level. From certain characteristic stabilized hysteresis, based on defined criteria, the data necessary for determination of the equations of characteristic curves of low-cycle fatigue have been collected, which show the difference between the values of exponents and coefficients defined by presented methodology depending on the method applied for the determination of stabilized hysteresis.

The results obtained represent practical contribution to estimation of the behaviour of low-alloy high-strength steel NN-70 exposed to the effects of low-cycle fatigue.

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